CHAPTER 3

EPA/NSF ETV
EQUIPMENT VERIFICATION TESTING PLAN
FOR THE REMOVAL OF INORGANIC CHEMICAL AND RADIONUCLIDE CONTAMINANTS BY ELECTRODIALYSIS AND ELECTRODIALYSIS REVERSAL

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1.0 APPLICATION OF THIS VERIFICATION TESTING PLAN

This document is the ETV Testing Plan for electrodialysis and electrodialysis reversal (ED/EDR). It should be noted that this Equipment Verification Plan is only applicable to electrically driven membrane processes.

In order to participate in the equipment verification process for ED/EDR, the Field Testing Organization (FTO) must adhere to the procedures and methods described in this study protocol and in the referenced ETV Protocol Document as guidelines for the development of a Product-Specific Test Plan (PSTP). The Procedures should generally follow those Tasks outlined herein, with changes and modifications made for adaptations to specific ED/EDR equipment. At a minimum, the format of the procedures written for each Task in the PSTP should consist of the following sections:

- Introduction
- Objectives
- Work Plan
- Analytical Schedule
- Evaluation Criteria

The primary treatment goal of the equipment employed in this Verification Testing Program is to achieve removal of inorganic or radioactive chemical constituents present in feedwater supplies. The Manufacturer may wish to establish a Statement of Performance Objectives (see General Approach below) that is based upon removal of target inorganic constituent(s) from feedwaters. The experimental design of the PSTP shall be developed to address that specific Statement of Performance Objectives established by the Manufacturer. Each PSTP shall include all of the included tasks, Tasks 1 to 5 as outlined below.

2.0 INTRODUCTION

Electrodialysis (ED) and Electrodialysis Reversal (EDR) are electrically driven membrane processes that are used for a broad number of water treatment applications ranging from sea water desalting processing, brackish water desalting, ultrapure water production and other specialized industrial applications. The most common application of ED/EDR is the production of potable water or demineralized industrial process water from brackish water sources. ED and EDR reduce the total dissolved solids in brackish water by electrically removing contaminants that exceed acceptable levels for drinking or process water.

ED/EDR is an electrochemical separation process in which ions are transferred through membranes from a diluting stream to a more concentrated solution as a result of direct electric current flow. Water flows through flow spacers between cation and anion selective membranes with the direct current between the anode and cathode serving as the driving force for the migration of ions. The membranes are "stacked", alternating the cation and anion permeable membranes thus allowing the ions to be removed or concentrated in the alternate water passages depending on the selectivity of the membrane. Cations are attracted to the negative electrode (cathode) and anions to the positive electrode (anode).

In order to establish appropriate operating conditions, the Manufacturer may be able to apply some experience with his equipment on a similar water source. This may not be the case for suppliers with new products. In this case, it is advisable to require a pre-test optimization period so that reasonable operating criteria can be established prior to Verification Testing. The need of pre-test optimization should be carefully reviewed with NSF, the FTO and the Manufacturer early in the process.

3.0 GENERAL APPROACH

Testing of equipment covered by this Verification Testing Plan will be conducted by an NSF-qualified FTO that is selected by the equipment Manufacturer. Analytical water quality work to be carried out as part of this Verification Testing Plan will be contracted with a laboratory certified by a state or accredited by a third partly organization (i.e. NSF) or the US Environmental Protection Agency (USEPA) for the appropriate water quality parameters.

For this Verification Testing, the Manufacturer shall identify in a Statement of Performance Objectives the specific performance criteria to be verified and the specific operational conditions under which the verification testing shall be performed. The Statement of Performance Objectives must be specific and verifiable by a statistical analysis of the data. Statements should also be made regarding the applications of the equipment, the known limitations of the equipment and under what conditions the equipment is likely to fail or under perform. There are different types of Statements of Performance Objectives that may be verified in this testing. Examples of two statements are:

1. *"This system is capable of achieving 90% fluoride removal during the operation using three electrical and three hydraulic stages at 90% water recovery in feedwater where fluoride levels are less than 10 mg/L and total hardness is less than 100 mg/L as $CaCO_3$ for water temperature ranging between 10º and 45ºC."*
2. *"This system is capable of producing a product water with less than 4 mg/L fluoride concentration during operation at recovery of 90 % (3-stage EDR) in feedwater with fluoride concentrations less than 10 mg/L and total hardness levels less than 100 mg/L as $CaCO_3$ for water temperature ranging between 10º and 45ºC."*

For each Statement of Performance Objectives proposed by the FTO and the Manufacturer in the PSTP, the following information shall be provided: percent removal of the targeted inorganic constituent; rate of treated water production; recovery; feedwater quality regarding pertinent water quality parameters; temperature; concentration of target inorganic constituent; and other pertinent water quality and operational conditions. During Verification Testing, the FTO must demonstrate that the equipment is operating at a steady-state prior to collection of data to be used in verification of the Statement of Performance Objectives. A mass balance using feed, product and waste stream concentrations must be used to confirm that steady state has been obtained and that none of the contaminant being removed is retained by the ED/EDR membrane stack(s).

This ETV Testing Plan is broken down into eight tasks, as shown in the Overview of Tasks section below. As noted above, Tasks 1 to 5 shall be performed by any manufacturer wanting to achieve verification of their equipment by NSF. The manufacturer shall provide full detail of the procedures to be followed in each Task in the PSTP. The Manufacturer shall specify the operational conditions to be verified during the Verification Testing Plan and provide water quality and performance data as needed to verify performance.

4.0 DEFINITION OF OPERATIONAL PARAMETERS

Faraday's Law (Equation 4.1): The passage of 96,500 amperes of electric current for one second will transfer one gram equivalent of salt. The quantity of 96,500 amperes-seconds is called a Faraday. Faraday's law is the basis for calculating the amount of electric current needed in a ED/EDR system for transferring a specific quantity of salts.

$$I = \frac{F^{*} \times Q_d \times \Delta N}{e \times n} \qquad \text{(Equation 4.1)}$$

where:
- I = Direct electric current in amperes
- F^{*} = Faraday's constant (96,500 ampere-seconds/equivalent)
- Q_d = Flow rate of the demineralized stream through the membrane stack (L/sec).
- ΔN = Change in normality of demineralized stream between the inlet and outlet of membrane stack (equivalents/L)
- e = Current efficiency
- n = Number of cell pairs

Ohm's Law (Equation 4.2): Ohm's Law states that the potential (E) of an electrical system is equal to the product of current (I) and the system resistance (R).

$$E = I \times R \qquad \text{(Equation 4.2)}$$

Resistance in Series Model (Equation 4.3): Several components make-up the resistance in an ED/EDR system in order to use Ohm's Law. The following resistance components must be included in calculating the system resistance using the applied voltage and amperage as sown in Equation 4.2 for a given salt removal and temperature condition.

$$R_{cp} = R_{cm} + R_{am} + R_c + R_{di} \qquad \text{(Equation 4.3)}$$

where:
- R_{cp} = resistance per unit area of one cell (ohm/cm^2)
- R_{cm} = resistance per unit area of cation membrane (ohm/cm^2)
- R_{am} = resistance per unit area of anion membrane (ohm/cm^2)
- R_c = resistance per unit area of concentrate stream (ohm/cm^2)
- R_{di} = resistance per unit area of demineralized stream (ohm/cm^2)

Electrical Resistance (Equation 4.4): The electrical resistance of an ED/EDR system is done using the initial resistance calculated using Equation 4.3. This is based on the initial water quality conditions, percent salt removals and water temperature. During operation of the ED/EDR system, the total stack electrical resistance is calculated using Equation 4.3 and normalized for feed water quality conditions, salt removals and temperature according to the manufacturer's normalization criteria. The change in electrical resistance during the demonstration program will be presented as follows and plotted against time:

$$R_d = R_t \div R_i \qquad \text{(Equation 4.4)}$$

where:

- R_d = resistance change per unit ED/EDR stack (ohm/cm^2)
- R_t = resistance of ED/EDR stack at time "t" (ohm/cm^2)
- R_i = resistance of ED/EDR stack at start-up (ohm/cm^2)

Current Efficiency (Equation 4.5): The efficiency of the current being used to transfer salts across the membrane can be calculated using the following equation:

$$e = \frac{F^* \text{ x } Q_d \text{ x } \Delta N \text{ x } 100}{I \text{ x } n} \qquad \text{(Equation 4.5)}$$

where:

- I = Direct electric current (amperes)
- F^* = Faraday's constant (96,500 ampere-sec./equivalent)
- Q_d = Flow rate of the demineralized stream through the membrane stack (L/sec).
- ΔN = Change in normality of demineralized stream between the inlet and outlet of membrane stack (equivalent/L)
- e = Current efficiency
- n = Number of cell pairs

Feed stream: This is the water quality that is fed into the membrane stack. Most of the feed stream is fed into the dilute stream (the stream that the salts are being removed from) and a lesser amount into the concentrate stream.

Dilute stream: Stream in the membrane stack that the salts are being removed from and eventually becomes the product water from the ED/EDR process.

Concentrate stream: Stream in membrane stack into which ions are transferred into and concentrated. This is also referred to as the brine stream. A portion of the concentrate stream is typically re-circulated through the membrane stack to maintain crossflow velocities through the membrane stack and increase water recovery.

Water Recovery (Equation 4.6): Total amount of water produced from the total amount of water used. Recovery can be calculated from the following equation:

$$\text{Recovery} = \frac{Q_{feed} - Q_{product}}{Q_{feed}} \times 100\% \qquad \text{(Equation 4.6)}$$

Solute Rejection (Equation 4.7): Solute rejection is controlled by a number of operational variables that must be reported at the time of water sample collection. Bulk rejection of a targeted inorganic chemical contaminant may be calculated by the following equation.

$$\%\,\text{Solute Rejection} = 100 \cdot \left[\frac{C_f - C_p}{C_f}\right] \qquad \text{(Equation 4.7)}$$

where: C_f = feedwater concentration of specific constituent (mg/L)
C_p = product concentration of specific constituent (mg/L)

Water and Solute Mass Balance (Equation 4.8): Calculation of solvent (water) mass balance shall be performed during Task 1 in order to verify the reliability of flow measurements through the membrane. Calculation of solute mass balance across the membrane system shall be performed as part of Task 3 in order to estimate the concentration of limiting salts at the membrane surface.

$$Q_f = Q_p + Q_c \qquad \text{(Equation 4.8)}$$
$$Q_f C_f = Q_p C_p + Q_c C_c$$

where: Q_f = feedwater flow to the membrane (gpm, L/h)
Q_p = product flow (gpm, L/h)
Q_c = concentrate flow (gpm, L/h)
C_f = feedwater concentration of specific constituent (mg/L)
C_p = product concentration of specific constituent (mg/L)
C_f = concentrate concentration of specific constituent (mg/L)

Solubility Product (Equation 4.9): Calculation of the solubility product of selected sparingly soluble salts will be required for the test plan in order to determine operational limitations caused by the accumulation of limiting salts at the membrane surface. Text book equilibrium values of the solubility product should be compared with solubility values calculated from the results of experimental Verification Testing, as determined from use of the following equation:

$$K_{sp} = g_A^x \left[A^{y-}\right]^x g_B^y \left[B^{x+}\right]^y \qquad \text{(Equation 4.9)}$$

where: K_{sp} = solubility product for the limiting salt being considered
γ = free ion activity coefficient for the ion considered (i.e., A or B)
[A] = molal solution concentration of the anion A for sparingly soluble salt A_xB_y
[B] = molal solution concentration of the anion B for sparingly soluble salt A_xB_y
x, y = stiochiometric coefficients for the precipitation reaction of A and B

Mean Activity Coefficient (Equation 4.10): The mean activity coefficients for each of the salt constituents may be estimated for the concentrated solutions as a function of the ionic strength:

$$\log g_{A,B} = -0.509 \cdot Z_A Z_B \sqrt{m} \qquad \text{(Equation 4.10)}$$

where: g = free ion activity coefficient for the ion considered (i.e., A or B)
Z_A = ion charge of anion A
Z_B = ion charge of cation B
m = ionic strength (cm^2/sec-volt-equivalent)

Ionic Strength (Equation 4.11): A simple approximation of the ionic strength can calculated based upon the concentration of the total dissolved solids in the feedwater stream:

$$m = (2.5 \cdot 10^{-5}) \cdot (TDS) \qquad \text{(Equation 4.11)}$$

where: μ = ionic strength (cm^2/sec-volt-eqiuvalent)
TDS = total dissolved solids concentration (mg/L)

5.0 OVERVIEW OF TASKS

The following section provides a brief overview of the tasks that shall be included as components of the Verification Testing Plan and PSTP for the removal of inorganic and radionuclide contaminates.

5.1 Task 1: Membrane Operation

The objective of this task is to evaluate ED/EDR membrane operation. The system performance shall be evaluated relative to the stated water quality goals and other performance characteristics specified by the Manufacturer. For Verification Testing purposes, the equipment shall be operated for a minimum of one, two-month testing period (see Testing Periods section below). Membrane productivity, rate of performance decline, and rejection capabilities will be evaluated at one set of operating conditions for the testing period. Membrane operations performance will also be evaluated in relation to feedwater quality and changes in quality resulting from seasonal or climatic changes. The impact of scale formation may also be addressed via addition of different pretreatment chemicals.

5.2 Task 2: Cleaning Efficiency

Materials are deposited on the membrane's surface and can create "hot spots" and cause loss of performance. Changes in feed water quality can cause increased fouling as well as operational changes. Chemical cleaning is used to recover the ED/EDR systems performance and remove foulants from the membrane's surface. The efficiency of the clean-in-place process determines how well the foulants are removed from the membranes and the long term performance of the system.

5.3 Task 3: Finished Water Quality

The objective of this task is to evaluate the quality of water produced by the membrane system and the removal of inorganic chemical contaminants achieved by the membrane system at the specified operational conditions. Multiple water quality parameters will be monitored during the two-month testing period, as specified by the FTO on behalf of the Manufacturer in the PSTP. At a minimum, monitoring of the water quality parameters shall include the following: pH, feedwater temperature, conductivity, total dissolved solids (TDS), alkalinity, Langlier Saturation Index (LSI), turbidity, total suspended solids (TSS), sulfate, sulfide, hardness, calcium, iron, manganese, aluminum, total organic carbon (TOC) and UV-254. Other water quality parameters that may include individual inorganic chemical or radionuclide contaminant concentrations will be selected and included in the PSTP at the discretion of the FTO and the Manufacturer. Water quality produced will be evaluated in relation to feedwater quality and operational conditions. Mass balances for selected inorganic constituents shall be calculated as needed to determine the accumulation of limiting salts on the membrane surface. Post-treatment capabilities of the equipment shall also be evaluated for pH adjustment and corrosion control in the product stream.

An overview of the equipment operational and production characteristics to be evaluated for each task of the Verification Testing Plan is provided in Table 1.

Table 1: Summary of Equipment Operational Characteristics to be Evaluated in Each Verification Testing Task

Equipment Operational Characteristic to be Evaluated	Task
1. Feedwater flow rate	1
2. Dilute stream flow rate	1
3. Concentrate flow rate	1
4. Off-Spec operational period	1
5. Inlet and Outlet pressures to membrane stack	1
6. Applied Stack Voltage	1
7. Applied Stack Amperage	1
8. Feedwater temperature	1
9. Electrode flush flow rate	1
10. Feed Water Conductivity	1
11. Feed Stream characterization	1
12. Product Water Conductivity	1
13. Power consumption	1
14. Current efficiency	1
15. Dilute stream characterization	3
16. Calculation of limiting salt concentrations	3
17. Waste stream characterization and range of waste stream flow rates	1,3

5.4 Task 4: Data Handling Protocol

The objective of this task is to establish an effective field protocol for data management at the field operations site and for data transmission between the FTO and the NSF during Verification Testing. Prior to the beginning of field testing, the database or spreadsheet design must be developed by the FTO and reviewed and approved by NSF. This will insure that the required data will be collected during the testing, and that results can be effectively transmitted to NSF for review. Relevant data will be prepared for inclusion in a final report at the conclusion of the Verification Testing Program.

5.5 Task 5: Quality Assurance Project Plan

An important aspect of Verification Testing is the Quality Assurance Project Plan (QAPP) developed for quality assurance and quality control. The objective of this task is to assure accurate measurement of operational and water quality parameters during membrane equipment Verification Testing.

6.0 TESTING PERIODS

The required tasks of the ETV Plan (Tasks 1 through 5) are designed to be completed during the two-month testing period, not including mobilization, shakedown and start-up. The Verification Testing Program requires that one testing period be performed for Verification Testing; however, it is recommended that additional testing periods be conducted in order to verify equipment performance under different conditions of feedwater quality and temperature. The schedule for equipment monitoring during the two-month testing period shall be stipulated by the FTO in the PSTP, and shall meet or exceed the minimum monitoring requirements included under Task 1 of this testing plan. The FTO shall ensure in the PSTP that sufficient water quality data and operational data will be collected to allow estimation of statistical uncertainty in the Verification Testing data, as described in the "EPA/NSF ETV Protocol For Equipment Verification Testing For Removal Of Inorganic Constituents: Requirements For All Studies", Section 4.5. The FTO shall therefore ensure that sufficient water quality and operational data are collected during Verification Testing for the statistical analysis described herein.

The recommendation for Verification Testing beyond the required two-month testing period is based on evaluation of equipment performance under different feedwater quality conditions that may be experienced annually. For example, climatic changes between rainy and dry seasons may produce substantial variability in feedwater turbidity and TOC for surface water sources. In addition, seasonal changes may also affect groundwater source quality by introducing variability in feedwater pH and variations in concentrations of TDS and specific inorganic chemical constituents. Cold weather operations can be an important component of seasonal water quality testing because of the impact of cold temperatures (1°C to 5°C) on water viscosity, membrane selectivity and salt diffusion process. In particular, for membrane process treatment equipment, factors that can influence treatment performance include:

- feedwaters with high seasonal concentrations of inorganic constituents and TDS. These conditions may increase finished water concentrations of inorganic chemical contaminants and may promote precipitation of inorganic materials in the membrane;
- feedwaters with variable pH; increases in feedwater pH may increase the tendency for precipitation of sparingly soluble salts in the membrane element and may require variable operational strategies.
- excessive levels of hydrogen sulfide, iron, manganese and aluminum must be removed prior to the ED/EDR unit;
- cold water, encountered in winter or at high altitude locations;
- high concentrations of natural organic matter (measured as TOC), which may be higher in some waters during different seasons;
- high turbidity, often occurring in spring, as a result of high runoff resulting from heavy rains or snowmelt.

It is highly unlikely that all of the above problems would occur in a water source during a single two-month period. Therefore, additional testing beyond the required two months of testing may be used for fine-tuning of membrane performance or for evaluation of additional operational conditions. During each testing period, Tasks 2 and 3 (evaluation of cleaning efficiency and finished water quality) can be performed concurrent with Task 1, the membrane operation testing procedures.

7.0 TASK 1: MEMBRANE OPERATION

7.1 Introduction

Membrane operation will be evaluated in Task 1, with quantification of electrical resistance, current efficiency and differential pressure. The rate of electrical resistance increase will be used to demonstrate membrane performance at the specific operating conditions to be verified. The operational conditions to be verified shall be specified by the FTO in terms of a temperature and salt removal corrected electrical resistance value (e.g., electrical resistance for % salt rejection at 20 °C per number of cell pairs) before the initiation of the Verification Testing Program.

Monitoring in Task 1 shall be focused on determining the operational characteristics such as those indicated in Table 2 (e.g.: current efficiency, electrical resistance, recovery, etc.). The actual operational parameters monitored will depend upon the type of Statement of Performance Objectives made in the PSTP, or other factors applicable to the technology that provide effective treatment of the feedwater. The FTO shall establish the testing conditions to be evaluated for Task 1 in the PSTP. An NSF field inspection of equipment operations and sampling and field analysis procedures may be carried out during the initial test runs in Task 1.

The rate of the electrical resistance increase is a function of water quality and operational strategy. Many factors may influence performance decline with ED/EDR membranes including inorganic scaling, particulate or organic fouling, biofouling, and other factors. In Task 1, electrical resistance increase shall be monitored to evaluate operational trends. Chemical characterization of the feedwater and dilute water stream with calculation of membrane rejection capabilities will be performed as part of Task 3. In addition, calculation of the operational limitations caused by limiting salt concentrations will be performed in Task 3. The testing runs conducted under Task 1 shall be performed in conjunction with Tasks 2 and 3. With the exception of the additional testing periods conducted at the FTO's discretion, no additional membrane test runs are required for performance of Tasks 2 and 3.

Any pretreatment included in an ED/EDR or other treatment system designed for inorganic contaminant removal shall be considered to be an integral part of the membrane treatment system and shall not be tested independently. In such cases, the system shall be considered as a single unit and the pretreatment process shall not be separated for optional evaluation purposes. The definition of pretreatment processes shall NOT include scaling control, corrosion control, and treatment for stabilization of ED/EDR-treated waters, as these treatments may be considered integral to the operation of the ED/EDR system.

7.2 Experimental Objectives

The objectives of Task 1 are to demonstrate the following: 1) the appropriate operational conditions for the membrane equipment; 2) the feedwater recovery achieved by the membrane equipment at the designated operational conditions; and 3) the rate of electrical resistance increase observed over extended ED/EDR membrane system operation during the two-month testing period. Task 1 is also intended to provide in operational power consumption information that can be used to develop cost estimates for operation and maintenance of the equipment. Complete chemical and physical characterization of the feedwater, concentrate stream and treated waters produced by the system, with calculation of limiting salt concentrations will be performed as part of Task 3.

It should be noted that the objective of this task is not process optimization, but rather verification of membrane operation at the operating conditions specified by the FTO, as pertains to power consumption and salt removals per stage. Verification of membrane operation under the conditions specified in the Statement of Performance Objectives shall also apply to conditions that are considered less challenging to the ED/EDR system. Examples of conditions considered less challenging may include lower salt rejections and lower system recoveries.

7.3 Work Plan

Mobilization and start-up of equipment shall be performed prior to the initiation of Task 1 testing. Furthermore, the ED/EDR membrane treatment system shall have achieved a condition of steady-state operation prior to the start of Task 1 testing. The FTO shall clearly describe in the PSTP the protocol for start-up of the membrane system, as well as operations and maintenance issues that may arise during mobilization and start-up.

After set-up and shakedown of the membrane equipment, ED/EDR operation should be established at the operational conditions established by the Statement of Performance Objectives. The membrane system shall be operated for a minimum of two months. A summary of the operational parameters to be recorded during Task 1 and the minimum frequency of monitoring are presented in Table 2. The FTO shall provide in the PSTP the necessary methods for monitoring of the operational parameters presented in Table 2. Additional monitoring of feedwater chemistry shall be performed during Verification Testing, as described below in Table 2.

Table 2: Task 1 Required Minimum Operating Data

Operational Parameter	Action, Monitoring Frequency
Dilute-in, electrode flush and concentrate make-up flow rates	Check and record twice daily. Adjust when 5% above or below target. Record both before and after adjustment.
Membrane Stack Inlet and Outlet Pressures (for each ED/EDR system)	Check and record twice daily.
Voltage and Amperage for + and - operational (for each electrical stage of the ED/EDR system)	Check and record twice daily
Voltage drop per inch of stack	Check and record weekly.
Recycle Ratio to obtain target Recovery	Check and record twice daily. Adjust when 2% above or below target.
Total Dissolved Solids Concentration in Feedwater, Concentrate, Product (for each stack of the ED/EDR system)	Calculation of salt normality gradient on daily basis. (Calculation per Equation 4.4, Section 4).
Feedwater Temperature	Record twice daily
Concentrate composition for disposal	Sample waste stream once during the minimum two-month testing period.
Concentrate and product flow rate	Check and record flow streams twice daily.

Determination of optimal membrane operating conditions for a particular water could potentially require as long as one year of operation. For Task 1 however, each set of operating conditions shall be maintained for the two-month testing period (continuous 24-hour operation). At a minimum, the membrane shall be chemically cleaned according to Manufacturer's specifications at the conclusion of the two-month testing period. At this time, the cleaning efficiency shall be determined per the requirements outlined in Task 2.

If substantial electrical resistance increase occurs at the specified operating conditions before the two-month operating period is complete, adjustments to the operational strategy shall be made. Decisions on which adjustments should be made shall be based upon the Manufacturer's experience and consultation with the FTO conducting the study. Adjustments in chemical addition (such as pH adjustment) shall not be considered to constitute changes in the overall operational strategy, as mentioned above. The FTO shall also specify the run termination criteria for the particular ED/EDR membrane equipment being tested under the Verification Testing Program. For example, the termination criteria may be defined as a 5% or 10% increase in electrical resistance, a drop in the percent solute rejection, or an increase in stack differential pressure to a specific value. In the case that fouling and electrical resistance increase occurs in a shorter time than the two-month testing period, the membrane shall be chemically cleaned and the operating or pretreatment conditions shall be adjusted. After these conditions are changed, the system would be operated until the completion of the two-month testing period. Because only one testing period shall be required in this Verification Testing Plan, the FTO shall specify the primary salt rejection levels at which the equipment is to be verified.

Concentrate streams and other waste streams generated by the membrane equipment must be completely characterized during Task 1 testing. The FTO shall completely describe and provide general characterization of the waste streams that are generated by the ED/EDR membrane treatment system in the PSTP, including pH, temperature, calcium, sulfate, TDS, alkalinity, TSS, disinfectant residual and any other parameter regulated in the waste stream. The FTO shall also discuss the applicable potential waste stream disposal issues in the PSTP, including disposal to the sewer or receiving waters.

Testing of additional operational conditions may be included in the Verification Testing Program at the discretion of the Manufacturer and their designated FTO. Testing of alternate operational conditions shall be performed by including one or more one-month testing period beyond the two-month testing periods required by the Verification Testing Program. Additional testing periods may be included to demonstrate membrane performance at different operational conditions or under different feedwater quality conditions. The FTO on behalf of the Manufacturer shall perform testing with as many different water quality conditions as desired for verification status.

This Membrane ETV Testing Plan has been written with the aim to balance the costs of verification with the benefits of testing the ED/EDR process over a wide range of operating conditions. Given that it may take more than one month to observe a significant electrical resistance increase in ED/EDR systems, examination under a wide range of operating conditions would be prohibitively expensive for the membrane Manufacturer. Therefore, this Verification Testing Plan requires that one set of operating conditions be tested during the two-month testing period. It shall be furthermore understood that beyond the single set of verification operating conditions, membrane operation that occurs at lower salt rejections or a lower recovery shall also constitute a verifiable condition.

7.4 Analytical Schedule

7.4.1 Operational Data Collection

Measurement of membrane performance parameters shall be monitored a minimum of 2 times per day, as indicated in Table 2. Monitoring shall be performed for each stage in the ED/EDR system. Temperature measurements shall be made on a daily basis in order to provide data for temperature correction of electrical resistance and for reporting of solute rejection (addressed in Task 3).

In an attempt to calculate costs for operation of membrane equipment, power costs for operation of the membrane equipment shall also be monitored and recorded by the FTO a minimum of 2 times per day, as indicated in Table 2. Furthermore, the costs of chemical addition shall be estimated by measurement of chemical usage through recording the day tank concentration, daily volume consumption and unit cost of chemicals.

7.4.2 Feedwater Quality Limitations

The characteristics of feedwater used during the two-month testing period (and any additional testing periods) shall be explicitly reported with the compiled results from electrical resistance, stack pressure drop and recovery monitoring. Accurate reporting of such feedwater characteristics as pH, temperature, conductivity, TDS, alkalinity, turbidity, sulfide, sulfate, iron manganese, aluminum calcium, hardness, TSS, and TOC concentration is critical for the Verification Testing Program, as these parameters may substantially influence the range of achievable membrane performance and treated water quality under variable raw water quality conditions. The TDS concentrations in the feedwater, product and concentrate streams shall be used to calculate the salt (Equation 4.4) removals through the membranes on a daily basis. Salt removal value shall then be used for calculation of current efficiency on a daily basis. Specific monitoring requirements for feedwater quality shall be stipulated in Task 3.

7.5 Evaluation Criteria and Minimum Reporting Requirements

- General operational performance
  - ⇒ Graph of change in electrical resistance (Equation 4.4) normalized to 20°C or 25°C and corrected for salt removals vs. time over the two-month testing period. Graphs showing time-dependent change of experimental parameters will be defined as temporal profiles. One temporal profile graph of electrical resistance shall be provided for each set of operational conditions and/or water qualities evaluated during Verification Testing.
  - ⇒ Temporal profile of differential pressure across each membrane stack over the two-month testing period. One temporal profile graph shall be provided for each set of operational conditions and/or water qualities evaluated during Verification Testing.
  - ⇒ Temporal profile of water recovery (Equation 4.6) over the two-month testing period. One temporal profile graph shall be provided for each set of operational conditions and/or water qualities evaluated.
- Power consumption
  - ⇒ Provide table of energy requirements, DC current efficiency, motor efficiency and consumed amperage for the testing period(s), as measured for each set of operational conditions.
- Concentrate stream characterization
  - ⇒ Provide table of concentrate stream quality parameters measured during the two-month testing period.

8.0 TASK 2: CLEANING EFFICIENCY

8.1 Introduction

During and following the test runs of Task 1, the membrane equipment may require chemical cleaning to restore membrane productivity. At a minimum, one cleaning shall be performed at the conclusion of the two-month period of required testing. In the case that the membrane does not fully reach termination criteria as specified by the Manufacturer in Task 1, chemical cleaning shall be performed after the two-month testing period. Measurement of membrane performance parameters at one set of operational conditions shall be made before and after cleaning.

8.2 Experimental Objectives

The objective of Task 2 is to evaluate the effectiveness of chemical cleaning for restoring the electrical resistance of the membrane system. Evaluation of the chemical cleaning procedure will be useful in confirming that standard Manufacturer-recommended cleaning practices are sufficient to restore membrane productivity. Furthermore, such testing may determine if the chemical cleaning procedure degrades the process in terms of its rejection capabilities for inorganic and radionuclide chemical contaminants. Cleaning chemicals and cleaning routines shall be adopted from the recommendations of the Manufacturer; this task is considered a "proof of concept" effort, not an optimization effort. It should be noted that selection of a chemical cleaning procedure is typically dependent upon the specific feedwater quality. The testing plan should permit evaluation of cleaning solutions that are considered optimal for the selected feedwaters. If the Manufacturer determines that a pre-selected cleaning formulation is not effective, the testing plan should allow the Manufacturer to modify it.

8.3 Work Plan

The membrane systems may experience electrical resistance increase during the membrane test runs conducted for Task 1. At the conclusion of the two-month testing period, the equipment shall be utilized for the cleaning assessments. Each system shall be chemically cleaned using the recommended cleaning solutions and procedures specified by the Manufacturer. After each chemical cleaning of the equipment, the system shall be restarted and the initial conditions of operation, electrical resistance, salt rejection percentage, recovery and specific inorganic and radionuclide contaminant rejection capabilities shall be tested.

The Manufacturer and their designated FTO shall specify in detail the procedure(s) for chemical cleaning of the membranes. At a minimum, the following shall be specified:

- cleaning chemicals
- quantities and costs of cleaning chemicals
- hydraulic conditions of cleaning
- time duration of each cleaning step
- initial and final temperatures of chemical cleaning solution
- quantity and characteristics of residual waste volume to be disposed
- recommended methods and considerations for disposal of residual cleaning waste

- procedure for tearing down and rebuilding ED/EDR membrane stack

In addition, detailed procedures describing the methods for pH neutralization of the used acid or alkaline cleaning solutions should be provided along with information on the proper disposal method for regulated chemicals. A description of all cleaning equipment and its operation shall be included in the PSTP prepared by the FTO.

8.4 Analytical Schedule

8.4.1 Operational Data Collection

Flow rates, pressures, voltage, amperage, recovery, and temperature data shall be collected during the cleaning procedure if possible and shall be recorded immediately preceding system shutdown. At the conclusion of each chemical cleaning event and immediately upon return to membrane operation, the initial operating conditions of salt rejection, electrical power, flow rate, recovery, ED/EDR stack voltage probe readings, and temperature shall be recorded and the electrical resistance calculated.

The efficacy of chemical cleaning shall be evaluated by the recovery of temperature-adjusted electrical resistance after chemical cleaning as noted below, with comparison drawn from the cleaning efficacy achieved during previous cleaning evaluations (if available). Comparison between chemical cleanings shall allow evaluation of the potential for irreversible loss of performance. Analysis of feedwater and dilute stream quality in subsequent runs shall also be used to evaluate any loss in membrane rejection capabilities caused by chemical cleaning.

Two primary indicators of cleaning efficiency and restoration of membrane productivity will be examined in Task 2. These are conditional on the temperature and ionic strength remaining constant or appropriately adjusted for changes in these two parameters.

1) The immediate recovery of membrane performance, as expressed by the ratio between the final electrical resistance value (R_f) and the initial electrical resistance (R_i) measured for the subsequent operational run:

$$\text{\% Increase of Original Electrical Resistance} = 100 * [\ 1 - (R_i \div R_f)]$$

where: R_f = resistance of ED/EDR stack at prior to cleaning (ohm/cm^2)
R_i = resistance of ED/EDR stack at start-up (ohm/cm^2)

2) The reduction in differential pressure across the membrane stack(s), as expressed by the ratio between the initial differential pressure for any given run (dP_i) divided by the final differential pressure measured at the initiation of operation for the final run in a series (dP_f):

$$\text{\% Increase of Original Differential Pressure} = 100 * [\ 1 - (dP_i \div dP_f)]$$

where: dP_f = differential pressure of ED/EDR stack at prior to cleaning (psid)

dP_i = differential pressure of ED/EDR stack at start-up (psid)

8.4.2 Sampling

The temperature, pH, conductivity, TDS, TOC, aluminum, calcium, sulfate, iron, manganese, and turbidity of each cleaning solution shall be measured and recorded during various periods of the chemical cleaning procedure. In addition, in the case that the cleaning solution employs an oxidant, such as chlorine, the concentration of the oxidant both before and at the end of the cleaning should be measured. Notes recording the visual observations (color, degree of suspended matter present) shall also be provided by the FTO.

8.5 Evaluation Criteria and Minimum Reporting Requirements

The minimum reporting requirements shall include presentation of the following results:

- Electrical Resistance recovery

⇒ Provide table of post cleaning electrical resistance recoveries during the two-month period of operation

- Differential Pressure recovery

⇒ Provide table of differential pressure recovery described above for chemical cleaning procedures performed during the two-month period of operation

- Assessment of irreversible increase of electrical resistance and estimation of usable membrane life for costing purposes.

9.0 TASK 3: FEEDWATER AND TREATED WATER QUALITY MONITORING

9.1 Introduction

Water quality data for the feedwater, the membrane product and concentrate streams shall be collected during the membrane test runs conducted as part of Task 1. No additional test runs shall be performed for Task 3 to acquire data on feedwater and treated water quality. The requirements for monitoring of water quality parameters in the feedwater, product and concentrate streams shall be clearly specified by the FTO in the PSTP according to the objectives of the Verification Testing program and the Statement of Performance Objectives. The specific water quality goals and the target removal goals for the membrane equipment shall also be recorded in the PSTP. A list of the minimum number of water quality parameters to be monitored during equipment Verification Testing in this Testing Plan is provided in Table 3. A list of the potential water quality parameters for additional monitoring is provided in Table 4 for the feedwater, the membrane product and concentrate streams. The actual water quality parameters selected for testing and monitoring during equipment Verification Testing shall be explicitly stipulated by the FTO in the PSTP.

9.2 Experimental Objectives

The objective of this task is to assess the ability of the membrane equipment to demonstrate the treatment and/or rejection capabilities indicated in the PSTP Statement of Performance Objectives. Mass balances shall be performed as part of Task 3 in order to evaluate the concentration of removed species during membrane system operation. Calculation of the recovery limitation caused by limiting salts will be performed to determine the impact of feedwater quality on membrane operation. Statistical analysis, as described in the "EPA/NSF ETV Protocol For Equipment Verification Testing For Removal Of Inorganic Constituents: Requirements For All Studies" (Section 4.5: Recording Statistical Uncertainty) is only required for those water quality parameters that shall be monitored on a weekly basis during each Verification Testing period.

9.3 Work Plan

The Manufacturer through their designated FTO shall identify the equipment rejection capabilities for selected inorganic chemical and radionuclide contaminants in the Statement of Performance Objectives provided in the PSTP. The Statement of Performance Objectives shall clearly establish the specific performance criteria to be verified and the specific operational conditions under which the Verification Testing shall be performed. For each Statement of Performance Objectives proposed by the FTO, the following information shall be provided: percent removal of the targeted inorganic constituent per stage, rate of treated water production; recovery; feedwater quality regarding pertinent water quality parameters; temperature; concentration of target inorganic or radionuclide constituent; and other pertinent water quality and operational conditions. Two examples of acceptable Statements of Performance Objectives are provided in Section 3.0. The Statement of Performance Objectives prepared by the Manufacturer and their designated FTO shall also indicate the range of water quality under which the equipment can be challenged while successfully treating the feedwater, as indicated by examples in Section 3.0.

Monitoring of water quality parameters in the feedwater, product and concentrate water streams shall allow calculation of percent rejection of the measured parameters and targeted inorganic chemical or radionuclide contaminants for the specific operational conditions evaluated. Estimation of the percent rejection of selected inorganic water quality parameters shall be based upon the equation for solute rejection provided in the section titled Definition of Operational Parameters, Equation 4.7.

Many of the water quality parameters described in this task shall be measured on-site by the NSF-qualified FTO. Analysis of the remaining water quality parameters shall be performed by a state-certified or third party- or EPA- accredited, analytical laboratory. The methods to be used for measurement of water quality parameters are identified in Tables 3 and 4. Where appropriate, the Standard Methods reference numbers and EPA method numbers for water quality parameters are provided for both the field and laboratory analytical procedures. A number of the analytical methods utilized in this study for on-site monitoring of feedwater and product water qualities are further described in Task 5, Quality Assurance Project Plan.

For the water quality parameters requiring analysis at a state-certified or third party- or EPA-accredited laboratory, water samples shall be collected in appropriate containers (containing necessary preservatives as applicable) prepared by the, off-site laboratory. These samples shall be preserved, stored, shipped, and analyzed in accordance with appropriate procedures and holding times, as specified by the analytical lab. Required information will be included on the "chain-of-custody" provided by the laboratory for all samples.

It should be noted that the membrane equipment participating in the Verification Testing Program for inorganic or radionuclide contaminant removal may be capable of achieving multiple water treatment objectives. Although this Testing Plan is oriented towards removal of inorganic and radionuclide contaminants, the Manufacturer may want to look at the treatment system's removal capabilities for additional water quality parameters.

9.4 Analytical Schedule

9.4.1 Feedwater, Product and Concentrate Characterization

During the two-month testing period, the feedwater, product and concentrate water streams shall be characterized at a single set of operating conditions indicated in the Statement of Performance Objectives. The minimum water quality monitoring requirements for this Verification Testing plan are provided in Table 3.

Table 3: Minimum Required Water Quality Sampling

Parameter	Sampling Frequency	Test Stream to be Sampled	Standard Method	EPA Method
pH	1/Day	Feed, Product	4500 H_+	150.1/150.2
Temperature	2/Day	Feed	2550 B	
Conductivity	2/Day	Feed, Prod., Conc.	2510 B	
TDS	1/Week	Feed, Prod., Conc.	2540 C	
Alkalinity	1/Month	Feed, Prod., Conc.	2320 B	
Langlier Saturation Index (LSI)	1/Month	Feed, Prod., Conc.	calculated	
Turbidity	1/Month	Feed, Prod., Conc.	2130 B	180.1
TSS	1/Month	Feed, Prod., Conc.	4500-NH_3 G	
TOC	1/Month	Feed, Prod., Conc.	5310 C	
Selected Inorganic Constituents (see Table 4)	3/Week	Feed, Prod., Conc.		

In addition, the FTO (on behalf of the Manufacturer) shall indicate in the PSTP the specific target inorganic chemical contaminants that shall be monitored in the Verification Testing Program per the Statement of Performance Objectives. A list of the potential inorganic chemical contaminants that may be included in this Verification Testing program is included in Table 4. The recommended monitoring frequency for these inorganic chemical contaminants shall be a minimum of three times per week distributed evenly through the week period.

Table 4: List of Inorganic Chemical Contaminants for Verification Testing

Parameter	Standard Method	EPA Method
Aluminum	3500 Al	202.2
Barium	3500 Ba	208.1
Cadmium	3500 Cd	213.2
Calcium	3500 Ca	215.2
Chloride	4500 Cl^-	325.1
Chromium	3500 Cr	218.2
Fluoride	4500 F^-	340.1
Iron	3500 Fe	236.1
Manganese	3500 Mn	243.1
Magnesium	3500 Mg	242.1
Nitrate	4500 NO_3^{-2}	352.1
Nitrite	4500 NO_2^{-2}	354.1
Sodium	3500 Na B	273.1
Strontium	3500 Sr	200.7
Sulfate	4500 SO_4^{-2}	375.4
Sulfide	4500 S^2	376.1
Other Inorganic Chemical Contaminants	TBD*	TBD
Optional:		
UV absorbance	5910 B	-
Total Trihalomethanes	5710	524.2
Haloacetic Acids	5710	552.1

* TBD - to be determined

9.4.2 Water Quality Sample Collection

Water quality data shall be collected at the specified intervals during each testing period. The minimum monitoring frequency for the minimum required water quality parameters is provided in Table 3. A minimum monitoring frequency of three per week shall be adopted for additional inorganic chemical contaminants to be included in the Verification Testing Program. At the discretion of the Manufacturer and the designated FTO, the water quality sampling program may be expanded to include any number of water quality parameters and an increased frequency of water quality parameter sampling. Sample collection frequency and protocol shall be defined explicitly by the FTO in the PSTP. To the extent possible, analyses for inorganic water quality parameters shall be performed on water sample aliquots obtained simultaneously from the same sampling location, in order to ensure the maximum degree of comparability between water quality analytes.

The TDS concentrations in the feedwater, product and concentrate streams shall be used to calculate the ionic strength of the feedwater and concentrate streams, as well as salt rejections by the membrane stack on a daily basis. Salt rejection gradient value shall then be used for calculation of electrical resistance and current efficiency on a daily basis. Mass balances for specified water quality parameters shall also be calculated at a frequency (minimum of once weekly) designated by the FTO. Calculation of the potential for recovery limitation based upon limiting salt concentrations shall also be performed at a frequency (minimum of once weekly) designated by the FTO.

9.5 Evaluation Criteria and Minimum Reporting Requirements

- Percent removal of inorganic chemical constituents
  - ⇒ Provide temporal plot of concentrations of target inorganic constituents and TDS in the feedwater, product and concentrate water streams over the two-month period of operation. Relevant inorganic constituents for monitoring shall be specified by the FTO on behalf of the Manufacturer in the PSTP.
  - ⇒ Provide table with weekly values of percent removal of target inorganic constituents and other pertinent water quality parameters for the two-month period of operation. The equation shown in the section titled Definition of Operational Parameters shall be used to determine percent removal of all pertinent water quality parameters for Verification Testing by the FTO and Manufacturer.
  - ⇒ Conduct mass balances through the membrane testing system for specific water quality constituents (minimum of once weekly) as identified by the FTO in the PSTP. The mass balance equation presented in the section titled Definition of Operational Parameters shall be used to the mass of concentration of inorganic constituents in different water streams.
  - ⇒ Calculate limiting salt concentrations (via solubility product calculation Equation 4.9) for specific water quality constituents (minimum of once weekly) as identified by the FTO in the PSTP. The equation for solubility product calculation as presented in the section titled Definition of Operational Parameters (Equation 4.9) shall be used to compare with standard Solubility Product values to determine if the salt concentration is posing a limitation to operational system recovery.
  - ⇒ Provide voltage readings obtained from ED/EDR stack probing in Table form.
  - ⇒ Provide temporal plot of polarity readings for amps and volts applied to each stage over the two-month period.
  - ⇒ Develop and provide power consumption plotted in kWhr/1,000 gallons produced versus time for the two-month testing period.
  - ⇒ Provide chemical usage and other ED/EDR stack parts replacement costs over the two-month period.
- Individual water quality and removal goals specified by the Manufacturer
  - ⇒ Provide feed, product and concentrate concentrations of any measured water quality parameters in tabular form for the two-month period of operation.

10.0 TASK 4: DATA HANDLING PROTOCOL

10.1 Introduction

The data management system used in the Verification Testing program shall involve the use of computer spreadsheets and manual (or on-line) recording of operational parameters for the membrane equipment on a daily basis.

10.2 Experimental Objectives

The objectives of Task 4 are: 1) to establish a viable structure for the recording and transmission of field testing data such that the FTO provides sufficient and reliable data to NSF for verification purposes, and 2) to develop a statistical analysis of the data, as described in the document "EPA/NSF ETV Protocol For Equipment Verification Testing For Removal Of Inorganic Constituents: Requirements For All Studies."

10.3 Work Plan

The following protocol has been developed for data handling and data verification by the FTO. Where possible, a Supervisory Control and Data Acquisition (SCADA) system should be used for automatic entry of testing data into computer databases. Specific parcels of the computer databases for operational and water quality parameters should then be downloaded by manual importation into Excel (or similar spreadsheet software) as a comma delimited file. These specific database parcels shall be identified based upon discrete time spans and monitoring parameters. In spreadsheet form, the data shall be manipulated into a convenient framework to allow analysis of membrane equipment operation. At a minimum, backup of the computer databases to diskette should be performed on a monthly basis.

In the case when a SCADA system is not available, field testing operators shall record data and calculations by hand in laboratory notebooks. (Daily measurements shall be recorded on specially-prepared data log sheets as appropriate.) The laboratory notebook shall provide carbon copies of each page. The original notebooks shall be stored on-site; the carbon copy sheets shall be forwarded to the project engineer of the FTO at least once per week during the one-month testing period. This protocol will not only ease referencing the original data, but offer protection of the original record of results. Operating logs shall include a description of the membrane equipment (description of test runs, names of visitors, description of any problems or issues, etc.); such descriptions shall be provided in addition to experimental calculations and other items.

The database for the project shall be set up in the form of custom-designed spreadsheets. The spreadsheets shall be capable of storing and manipulating each monitored water quality and operational parameter from each task, each sampling location, and each sampling time. All data from the laboratory notebooks and data log sheets shall be entered into the appropriate spreadsheet. Data entry shall be conducted on-site by the designated field testing operators. All recorded calculations shall also be checked at this time. Following data entry, the spreadsheet shall be printed out and the print-out shall be checked against the handwritten data sheet. Any corrections shall be noted on the hard-copies and corrected on the screen, and then a corrected version of the spreadsheet shall be printed out. Each step of the verification process shall be initialed by the field testing operator or engineer performing the entry or verification step.

Each experiment (e.g., each membrane test run) shall be assigned a run number that will then be tied to the data from that experiment through each step of data entry and analysis. As samples are collected and sent to state-certified or third party- or EPA- accredited laboratories, the data shall be tracked by use of the same system of run numbers using chain-of-custody forms. Data from the outside laboratories shall be received and reviewed by the field testing operator. These data shall be entered into the data spreadsheets, corrected, and verified in the same manner as the field data.

As available, electronic data storage and retrieval capabilities shall be employed in order to maximize data collection and minimize labor hours required for monitoring. The guidelines for use of data-loggers, laptop computers, data acquisition systems etc., shall be detailed by the FTO in the PSTP.

11.0 TASK 5: QUALITY ASSURANCE PROJECT PLAN

11.1 Introduction

Quality assurance and quality control of the operation of the membrane equipment and the measured water quality parameters shall be maintained during the Verification Testing program. A Quality Assurance Project Plan detailing the quality assurance/quality control (QA/QC) procedures to be followed during Verification Testing shall be provided by the FTO as part of the PSTP.

11.2 Experimental Objectives

The objective of this task is to maintain strict QA/QC methods and procedures during the Equipment Verification Testing Program. Maintenance of strict QA/QC procedures is important, in that if a question arises when analyzing or interpreting data collected for a given experiment, it will be possible to verify exact conditions at the time of testing.

11.3 Work Plan

Equipment flowrates and associated signals should be documented and recorded on a routine basis. A routine daily walk through during testing shall be established to verify that each piece of equipment or instrumentation is operating properly. Particular care shall be taken to confirm that any chemicals are being fed at the defined flowrate into a flowstream that is operating at the expected flowrate, such that the chemical concentrations are correct.

In-line monitoring equipment such as flowmeters, etc. shall be checked to confirm that the readout matches with the actual measurement (i.e. flowrate) and that the signal being recorded is correct. The items listed are in addition to any specified checks outlined in the analytical methods and include volt and amperage reading equipment.

11.3.1 Daily QA/QC Verifications:

- Chemical feed pump flowrates (verified volumetrically over a specific time period)
- Flow rates to on-line analytical equipment (e.g., pH meter, conductivity meter, turbidimeter), if any (verified volumetrically over a specific time period).

11.3.2 Monthly QA/QC Verifications:

- In-line flowmeters/rotameters (clean equipment to remove any debris or biological buildup and verify flow volumetrically to avoid erroneous readings);
- On-line pH meters, conductivity meters, turbidimeters etc. (clean out reservoirs and re-calibrate, if employed)
- Differential pressure transmitters (verify gauge readings and electrical signal using a pressure meter);
- Tubing (verify good condition of all tubing and connections; replace if necessary)
- Volt and amperage meters (verify gauge readings and signal using calibrated hand-held meters).

11.4 Analytical Methods and Sample Collection

The analytical methods utilized in this Equipment Verification Testing Plan for on-site monitoring of feedwater, product and concentrate water quality are described in the section below. Use of either bench-top or on-line field analytical equipment will be acceptable for the Verification Testing; however, on-line equipment is recommended for ease of operation. Use of on-line equipment is also preferable because it reduces the introduction of error and the variability of analytical results generated by inconsistent sampling techniques.

11.4.1 pH

Analyses for pH shall be performed according to Standard Method 4500-H^+ and include temperature compensation. A three-point calibration of the pH meter used in this study shall be performed once per day when the instrument is in use. Certified pH buffers in the expected range shall be used. The pH probe shall be stored in the appropriate solution defined in the instrument manual.

11.4.2 Conductivity

Analyses for conductivity shall be performed according to Standard Method 2510 B. A three-point calibration of the conductivity meter used in Verification Testing shall be performed once per day when the instrument is in use. Certified conductivity solutions in the expected range shall be used. The probe shall be stored in the appropriate solution defined in the instrument manual.

11.4.3 Turbidity

Turbidity analyses shall be performed according to Standard Method 2130 with either an on-line or bench-top turbidimeter. During each testing period, the on-line and bench-top turbidimeters shall be left on continuously. Once each turbidity measurement is complete, the unit shall be switched back to its lowest setting. All glassware used for turbidity measurements shall be cleaned and handled using lint-free tissues to prevent scratching. Sample vials shall be stored inverted to prevent deposits from forming on the bottom surface of the cell.

The FTO shall be required to document any problems experienced with the turbidity monitoring instruments, and shall also be required to document any subsequent modifications or enhancements made to monitoring instruments.

On-line Turbidimeters: On-line turbidimeters may be used for measurement of turbidity during Verification Testing, and must be calibrated as specified in the instrument manufacturer's operation and maintenance manual. It will be necessary to periodically verify the on-line readings using a bench-top turbidimeter; although the mechanism of analysis is not identical between the two instruments, the readings should be comparable. Should the comparison suggest inaccurate readings, then all on-line turbidimeters should be re-calibrated. In addition to calibration, periodic cleaning of the lens should be conducted using lint-free paper, to prevent any particle or microbiological build-up that could produce inaccurate readings. Periodic verification of the sample flow shall also be performed using a volumetric measurement. Instrument bulbs shall be replaced on an as-needed basis. It should also be verified that the LED read-out matches the data recorded by the data acquisition system, if the latter is employed.

Bench-Top Turbidimeters: Grab samples of feedwater and oxidized/disinfected water may be analyzed using a bench-top turbidimeter. Readings from this instrument shall serve as reference measurements throughout the study. The bench-top turbidimeter shall be calibrated within the expected range of sample measurements at the beginning of equipment operation and on a weekly basis using primary turbidity standards of 0.1, 0.5, and 5.0 Nephlometric Turbidity Units (NTU). Secondary turbidity standards shall be obtained and checked against the primary standards. Secondary standards shall be used on a daily basis to verify calibration of the turbidimeter and to re-calibrate when more than one turbidity range is used.

The method for collecting grab samples shall be performed according to the following protocol: 1) running a slow, steady stream from the sample tap, 2) triple-rinsing a dedicated sample beaker in this stream, 3) allowing the sample to flow down the side of the beaker to minimize bubble entrainment, 4) double-rinsing the sample vial with the sample, 5) carefully pouring from the beaker down the side of the sample vial, 6) wiping the sample vial clean, 7) inserting the sample vial into the turbidimeter, and 8) recording the measured turbidity. For the case of cold water samples that cause the vial to fog preventing accurate readings, the vial shall be allowed to warm up by partial submersion in a warm water bath for approximately 30 seconds.

11.4.4 Analysis for Inorganic Chemical Contaminants

Methods to be employed for analysis of specific analytical parameters shall be explicitly identified by the FTO in the PSTP. The methods selected for analysis of all inorganic constituents shall comply with those described in the most recent edition of Standard Methods or should be considered a comparable EPA Method.

12.0 OPERATION AND MAINTENANCE

The following are recommendations for criteria to be included in Operation and Maintenance (O&M) Manuals for ED/EDR membrane systems that are designed to achieve removal of inorganic chemical constituents. Descriptions of the membrane equipment unit process shall be developed by the FTO on behalf of the Manufacturer and included in the PSTP. Appropriate parameters for system description shall include but not be limited to the following elements: standard design criteria, membrane process characteristics, pre-treatment requirements and post-treatment concerns. An overview of the pertinent membrane plant design information that may be required for the PSTP is provided in Table 5. A list of relevant membrane element characteristics is provided in Table 6. The following sections provide lists of maintenance and operations criteria that may be helpful for development of O&M Manuals for ED/EDR membrane systems.

Table 5: Membrane Plant Design Criteria Reporting Items

Parameter	**Value**
Number of Membrane Stacks	
Number Electrical Stages per Stack	
Number Hydraulic Stages per Stack	
Number Membrane Cell Pairs per Hydraulic Stage	
Recovery per Stack (%)	
Recovery for System (%)	
Design Product Flow (gpm)	
Initial Electrical Resistance (ohms) at 20 °C	
Maximum Flow Rate to a Stack (gpm)	
Minimum Flow Rate to a Stack (gpm)	
Pressure Loss per Stack (psi)	
Feed Stream TDS (mg/L)	
TDS Rejection (%)	
Rejection of Specific Inorganic Constituent (%)	

Table 6: Membrane Element Characteristics

Parameter	Value
Membrane Manufacturer	
Membrane Element Model Numbers (anion & cation)	
Size of Element Used in Study (e.g., 18"x40")	
Sales Price for 18"x40" cation membrane ($)	
Sales Price for 18"x40" anion membrane ($)	
Membrane Material of Construction (cation)	
Membrane Material of Construction (anion)	
Spacer Thickness (in)	
Sales Price for Electrode ($)	
Electrode Material of Construction	
Electrode Thickness (in)	
Design differential Pressure (psi)	
Design Salt Rejections per Stage (%)	
Variability of Design Salt Rejections (%)	
Design Electrical Resistance at 20 °C	
Design Recovery (%)	
Design Stack Feed Flow Velocity (ft/s)	
Maximum Flow Rate to Stack (gpm)	
Minimum Flow Rate to a Stack (gpm)	
Required Feed Flow to Electrode Flush Stream (gpm)	
Maximum System Recovery (%)	
Rejection of Reference Solute and Conditions of Test (e.g., Solute type and concentration)	
Variability of Rejection of Reference Solute (%)	
Acceptable Range of Operating Pressures (psi, bar)	
Acceptable Range of Operating pH Values	
Typical Pressure Drop across a Single Stack (psi)	
Maximum Permissible Turbidity	
Chlorine/Oxidant Tolerance	
Average voltage drop for new cell	
Suggested Cleaning Procedures	

12.1 Maintenance

The Manufacturer shall provide readily understood information on the recommended or required maintenance schedule for each piece of operating equipment such as:

- pumps

- valves, including detailed information on the valve configuration for cross-flow operation
- pressure gauges
- flow meters
- air compressors
- chemical feeder systems
- mixers
- motors
- instruments, such as streaming current monitors or turbidimeters
- water meters, if provided
- electrodes

The Manufacturer shall provide readily understood information on the recommended or required maintenance for non-mechanical or non-electrical equipment such as:

- tanks and basins
- in-line static mixers
- tubing and hoses

12.2 Operation

The Manufacturer should provide readily understood recommendations for procedures related to proper operation of the equipment. Among the operating aspects that should be discussed are the following issues:

ED/EDR System:

- control of feed flow and recycle flows to the membrane system and individual stages
- measurement of inlet/outlet pressures and product flows
- measurement of power usage for + and – polarity operation
- measurement of voltage probing in membrane stacks
- measurement/calculation of power and water flow operational parameters
- maintenance of proper stack weeping

Chemical cleaning:

- selection of proper chemical washing sequence
- proper procedures for dilution of chemicals
- monitoring of pH through chemical cleaning cycle
- rinsing of membrane system following chemical clean
- return of membrane system to service

Chemical feeders

- calibration check on flow meters and dosing pumps
- settings and adjustments -- how they should be made
- dilution of chemicals -- proper procedures
- proper dosage and control for ECIP and brine re-circulation feeds (if used)

Intermittent Operation:

- proper procedures for system shut-down and start-up
- safety checks of chemical concentrations prior to system shut-down
- safety checks of potential contaminant concentrations prior to system shut-down and start-up
- proper procedures for rinsing and disinfection of system following shut-down

Monitoring and Sampling Procedures:

- observation of feedwater or pretreated water salt rejection
- observation of power use increase
- proper monitoring procedures for measurement of product conductivity
- proper safety procedures

The Manufacturer should provide a troubleshooting guide; a simple check-list of what to do for a variety of problems including:

- no raw water (feedwater) flow to plant
- can't control rate of flow of water through equipment
- poor product quality
- identification of "hot spots" in membrane stack
- automatic operation (if provided) not functioning
- reduced percent solute rejection
- machine will not start and "Power On" indicator off
- machine will not start and "Power On" indicator on
- pump cavitation
- valve stuck or won't operate
- no electric power
- no chemical feed for ECIP or brine re-circulation
- membrane flow spacer plugged

12.3 Operability

The following are recommendations regarding operability aspects of systems that are designed to achieve removal of inorganic chemical and radionuclide contaminants. These aspects of plant operation should be included if possible in reviews of historical data, and should be included to the extent practical in reports of equipment testing when the testing is done under the ETV Program.

During Verification Testing and during compilation of historical equipment operating data, attention shall be given to equipment operability aspects. Among the factors that should be considered are:

- fluctuation of flow rates and pressures through membrane unit - the time interval at which resetting is needed (i.e., how long can feed pumps hold on a set value for the feed rate?)
- fluctuation of applied electrical volts and amps applied to each stage.
- presence of devices to aid the operator with flow control adjustment and chemical dosage selection:
  - ⇒ are continuous flow meters provided for monitoring of feedwater, product and concentrate re-circulation flows?
- Conductivity provided for monitoring of ED/EDR System product?
- does plant have multiple feed points for chemicals:

- ⇒ for ECIP
- ⇒ for concentrate recycle

- are electrical current measurements provided?
- is rate of flow of raw water measured?
- are chemical feeds paced with water flow?

Both the reviews of historical data and the reports on Verification Testing should address the above questions in the written reports. The issues of operability should be dealt with in the portion of the reports that are written in response to Tasks 1 & 2 of the Verification Testing Plan.

13.0 REFERENCES

Electrodialysis and Electrodialysis Reversal, American Water Works Association, AWWA M38, Denver, CO, 1995.

Electrodialysis – Electrodialysis Reversal Technology, Ionics Incorporated, Watertown, MA, 1984.

Standard Methods for the Examination of Water and Wastewater. 1999. 20th edition. APHA, AWWA, and WEF, Washington, D.C.

Water Treatment – Membrane Processes, American Water Works Association Research Foundation, Denver, CO 1996.